

Detrital Gold as a Deposit-Specific Indicator Mineral, British Columbia: Analysis by Laser-Ablation Inductively Coupled Plasma–Mass Spectrometry

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Introduction

The northern cordillera has been the focus of traditional prospecting for nearly 200 years. Placer-gold occurrences are widespread and have supported an industry that has underpinned many local economies. In some cases, further prospecting has identified significant in situ mineralization that has also been profitably exploited, but the relationship between placer gold and its source lode is less clear at other localities, either as a consequence of extensive surficial sediments or because complex solid geology provides several potential geological settings for source mineralization. Both these factors have constrained exploration in British Columbia (BC). The use of gold compositional studies has elevated the potential value of detrital gold from a simple physical marker to an indicator of the source style of mineralization. For example, regional studies in the Yukon and the Fortymile district of the Yukon and Alaska have identified the importance of gold derived from orogenic systems in local placer inventories, even when an intrusion-related source type has been proposed (Wrighton, 2013). This approach has also been used in BC to elucidate detailed variation in the mineralogy of detrital gold in the Cariboo gold district and to infer the relative importance of lode sources (Chapman and Mortensen, 2016). The alkalic copper-gold porphyries of BC are both potential sources of detrital gold and located within wider auriferous areas. Consequently, the region provides an excellent study area in which to explore the potential of gold compositional studies in the context of exploration in a challenging environment.

Exploration for porphyry mineralization is increasingly focused on techniques that can identify mineralization concealed by Quaternary cover. Studies of the trace-element mineralogy of minerals formed in porphyry systems (e.g.,

Bouzari et al., 2010, 2016; Celis et al., 2014; Pisiak et al., 2015) have identified mineralogical markers indicative of the environment of formation within an evolving magmatic-hydrothermal system. The overall aim of these studies has been to permit informed interrogation of heavy-mineral concentrates (HMC) collected during exploration campaigns.

Native gold grains derived from such mineralization may also be present in panned concentrates. However, the simple presence of gold grains is not necessarily indicative of derivation from the exploration target. For example, Kelley et al. (2011) reported that the nature of gold-dispersion trains in glacial sediments in the environs of the Pebble porphyry in Alaska may have been influenced by the influx of gold from different sources. The dispersion of particulate gold from the Mt. Polley porphyry deposit through glacial transport was investigated by Plouffe et al. (2013), who noted that the presence of a large, auriferous paleoplacer deposit lying stratigraphically below till near the deposit could have resulted in gold grains being recycled into the more recent sediments. The information flowing from the identification and character of particulate gold in HMC would be far greater if it were possible to establish its genetic origin.

Studies of gold-grain chemistry have been undertaken by several workers since the advent of the electron microprobe, which facilitates rapid determination of the major alloying elements (Ag, Cu, Hg, Pd) within native gold particles. Antweiler and Campbell (1977) identified systematic spatial variation in both Ag and Cu contents of native gold in the environs of Circle City, Alaska and speculated that gold composition was a consequence of the temperature at which the source mineralization was emplaced. Subsequent studies in important placer districts, such as the Cariboo (Mctaggart and Knight, 1993) and the Klondike (Knight et al., 1999), also identified variation in the alloy compositions of populations of gold grains collected from different localities. Knight et al. (1999) applied these data

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to speculate that some in situ sources of Klondike placer gold remained to be discovered.

In the late 1980s, the British Geological Survey developed a refined approach to gold-grain characterization that involved systematic screening of grain sections to identify inclusions of other minerals preserved within the gold grains. They successfully correlated inclusion suites with variation in alloy composition to refine the characteristics of populations of detrital gold grains. This approach of ‘microchemical characterization’ has been applied to gold from many localities worldwide, (e.g., Chapman et al., 2000, 2010; Chapman and Mileham, 2016), with a view to developing a global template by which detrital gold can act as an indicator for the source style of mineralization. The use of inclusions in the characterization process has permitted clarification of placer-lode relationships in the Lone Star area of the Klondike, where consideration of inclusion signatures distinguished between populations of gold from different sampling sites that were previously indistinguishable in terms of their alloy composition.

Although distinction between populations of grains derived from different mineralizing events and different source styles of mineralization are commonly identified using this approach, the methodology depends upon analyses of much larger gold grain populations than are routinely collected in HMC. Such gold-grain studies normally require a separate dedicated sampling exercise by personnel experienced in collecting gold particles in areas of low abundance. Any analytical method that could reduce the number of gold grains required to establish provenance would effectively remove this major barrier to using detrital gold as an indicator mineral.

The determination of trace metals by laser-ablation inductively coupled plasma–mass spectrometry (LA-ICP-MS) has only rarely been applied to particulate gold, principally because gold commonly contains mercury, which takes considerable time to be flushed through the instrument and is a major interference when the instrument is used for U-Pb isotopic dating of other minerals. Unlike many other LA-ICP-MS installations available in Canada and elsewhere, the equipment at Leeds is not used for dating by Pb determination, and thus may be routinely employed for gold analysis. The data flowing from LA-ICP-MS analysis would allow characterization of gold based on a far larger array of trace elements and at lower detection limits than is currently possible using electron microprobe (EMP) methods, but has the disadvantage that the method is destructive.

This project involves analysis of populations of gold grains from throughout BC whose microchemical signature has already been determined (Figure 1, Table 1). The aims of the project are to provide the first large-scale dataset that would allow:

- 1) evaluation of the suitability of LA-ICP-MS for gold analyses,
- 2) comparison of microchemical signatures with trace-element signatures, and
- 3) identification of any trace-element signatures diagnostic for gold formed in specific environments.

This paper contains the preliminary findings of this study, which commenced in August 2016. Analysis of some target sample suites is complete, while others remain to be analyzed. Consequently, it is not yet possible to interrogate the full database to answer points 1–3 (above).

Methodology

Sample Suites

Various sample suites studied in previous projects were available to the present study. They include those that underpinned studies of the Cariboo gold district (Chapman and Mortensen, 2016) and studies of gold derived from alkalic porphyry systems (Chapman and Mileham, 2016). Populations of gold grains previously collected had been mounted in resin blocks and polished to reveal grain core to facilitate earlier microchemical studies. It has not been possible to analyze every grain in all these collections because of the large numbers involved. Nevertheless, complete datasets will be generated for some sample populations that are considered important to the study. The samples analyzed are indicated in Table 1.

Analytical Method

Images of the polished block surface were used to identify each grain within each sample population, while enabled correlation of previous microchemical data with that obtained by laser-ablation inductively coupled plasma–mass spectrometry (LA-ICP-MS). The LA-ICP-MS system uses an Agilent 7500c quadrupole mass spectrometer, combined with a Geolas ablation system to determine the composition of individual grains. The Geolas ablation system uses a Compex 103 ArF excimer laser operating at a wavelength of 193 nm and delivering an energy density of up to 20 J/cm on the sample surface at a pulse frequency of up to 20 Hz, with spot sizes ranging from 5 to 160 µm. The ablated material is transported from the ablation cell to the ICP-MS us-

Figure 1. Locations of gold-grain sampling in central British Columbia: **a)** location of the Cariboo gold district (box; see part b) and sample locations near Kamloops (Afton mine, MINFILE 092INE023; Tranquille River placer, MINFILE 092INE106; and Cherry Creek) and in the Princeton area (Copper Mountain mine, MINFILE 092HSE001; Similkameen River placer, MINFILE 092HSE233; Whipsaw Creek placer, MINFILE 092HSE236; and Friday Creek); **b)** detail of sample locations in the Cariboo gold district (Spanish Mountain, MINFILE 093A 043; Mount Polley, MINFILE 093A 008); geology adapted from Mortensen and Chapman (2010); grid references for other placer localities provided in Table 1; place names with the generic in lower case are unofficial; refer to BC Geological Survey (2016) for MINFILE records.

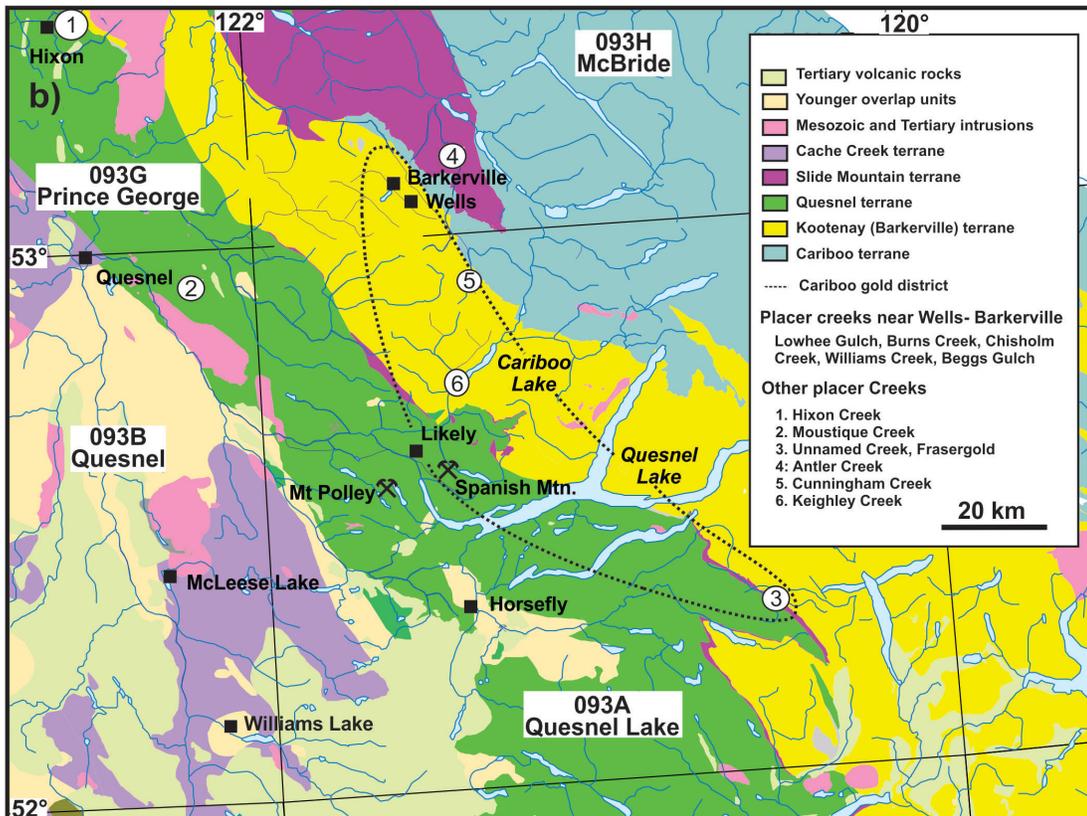
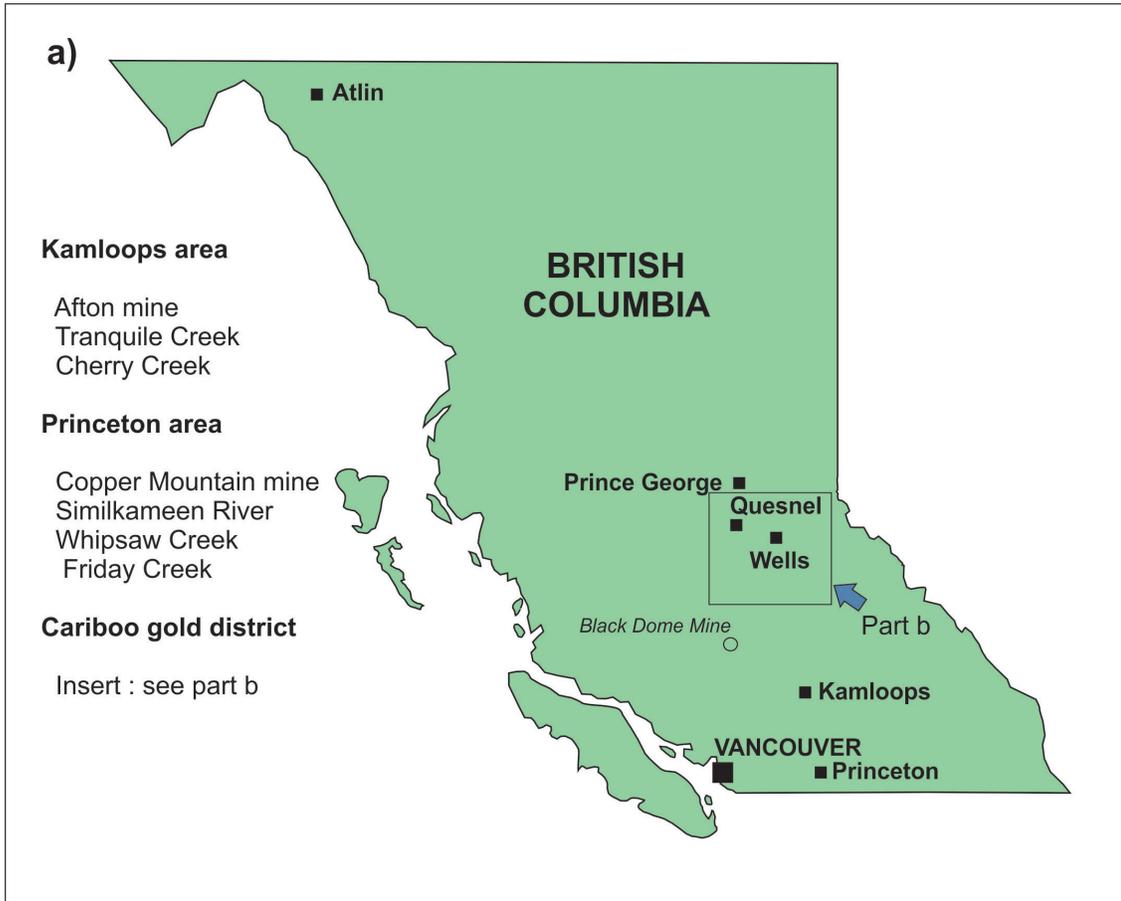


Table 1. Sample localities, indicating progress of the experimental program in the context of the original proposal.

Sample location	UTM Zone 10N, NAD 83		No. of grains	
	Easting	Northing	Identified ⁷	Analyzed ⁸
CGD: lode samples²				
Cow Mountain vein	596050	5883280	2*	0
Wells adit	595950	5883250	30	0
Warspite	601518	5876958	30	0
BC vein	596343	5883218	30	0
Myrtle	597414	5881788	24	0
Hibernia	586345	6011100	76	16
Midas adit	606400	5856400	22	0
Frasergold ⁵	665083	5797785	30	0
CGD: placer samples²				
Williams Creek	599830	5881613	54	41
Beggs Gulch	606300	5875500	30	30
Keighley Creek	604183	5849514	30	16
Amador Creek	588853	5876180	30	0
Burns Creek	590031	5881840	30	26
Lowhee Creek	596500	5883750	30	56
Antler Creek	606750	5871205	60	15
Cunningham Creek	610520	5865900	30	22
Dragon Creek	583016	5885903	12	26
Spanish Mountain ⁵	604674	5827518	30	30
Chisholm Creek	586791	5878197	0	20
Frasergold Creek	666389	5797008	28	8
Moustique Creek	569250	5873350	40	26
Hixon Creek	529328	5922040	30	54
Alkalic porphyry: lode samples³				
Mount Milligan (P)	434363	6109388	18	5
Mount Milligan (Pr)	434698	6109464	5	0
Mount Polley (P)	Wight Pit stockpile		16	6
Afton (P)	¹		4	0
Copper Mountain (P)	679873	5466653	5	2
Alkalic porphyry: placer samples³				
King Richard Creek	434721	6108928	30	36
Similkameen River	678215	5468502	60	117
Friday Creek ⁶	677785	5463800	30	54
Whipsaw Creek ⁶	677057	5471100	30	46
Cherry Creek	672106	5615716	30	42
Tranquille Creek	675305	5624270	40	62
Low sulphidation epithermal				
Black Dome ^{4,5}	535537	5685967	0	20

¹samples from Leeds University archive collection, labelled as 'Afton Pit'

²gold grains studied by Chapman and Mortensen (2016)

³grains studied by Chapman and Mileham (2016)

⁴sample obtained from The University of British Columbia collections

⁵co-ordinates taken from MINFILE reports

⁶approximate co-ordinates, as samples were donated from placer miners

⁷for study in proposal

⁸to date

Abbreviations: P, zone of potassic alteration; Pr, zone of propylitic alteration; CGD, Cariboo gold district (see Figure 1)

ing 99.9999% He flowing at 2 ml/min into a cyclone mixer, where it is combined with the Ar carrier gas flowing at 1.02 ml/min. The instrument can be operated in reaction-cell mode using 2.5 ml/min 99.9999% H₂ to remove interferences from ⁴⁰Ar on ⁴⁰Ca and from ⁵⁶ArO on ⁵⁶Fe; however, this also reduces the signal intensity of both the background and the analyte. In general, the target elements analyzed had low background signals and the only benefit would have been the ability to use the major ⁵⁶Fe isotope for analysis, but it was found that operating without the reaction cell enhanced sensitivity for the isotopes analyzed.

Figure 2 shows the effects of ablating gold grains for 150 laser pulses. The predominant feature is the rim of metal that has condensed on the surface around the ablation pit. This is much less than the volume of material that has been transported into the ICP-MS, but analysis of these rims does not indicate there has been any elemental fractionation between what has been transported and what has been condensed. As gold is easily ablated at the 193 nm wavelength, the laser energy was reduced to 6 J/cm and the pulse rate tuned to 5 Hz. The best analytical data are gained from conditions where a stable ablation profile is achieved for periods of around 10 seconds (Figure 3), as this allows the mass spectrometer to cycle through the elements a number of times to produce the most reproducible ratios relative to the internal standard element. At higher energies or higher pulse rates, the gold was ablated all the way through too quickly and analyses were less reproducible and accurate. As an estimate, it was found that 150 pulses was ablating the gold to a depth of around 100–120 µm. The lower en-

ergy did result in a lower ablation rate and, accordingly, a lower ICP-MS response, but this was not overly significant. The size of the laser pulse determined the depth to which ablation was possible and hence the duration of the ICP-MS elemental signal. For spot sizes of 5, 10 and 15 µm, there was an initial signal whose duration increased with the size of spot but rapidly diminished prior to the selected target of 150 laser pulses. The laser energy could penetrate to the bottom of the smaller diameter laser pits as effectively and hence ablation of the gold ceased. Therefore, all the gold grains were analyzed with spot diameters of 25–100 µm, with 50 µm being the most frequent size used, to ensure ablation continued for the full 150 pulses.

Calibration and Quantification

The gold grains were analyzed for a large number of elements to see which were detectable and to provide an appraisal of which would be useful in distinguishing different deposits and metallogenic types, and potentially be indicative of processes operating during precipitation. The suite of elements was ²⁷Al, ²⁹Si, ³²S, ⁴⁷Ti, ⁵¹V, ⁵³Cr, ⁵⁵Mn, ⁵⁷Fe, ⁵⁹Co, ⁶⁰Ni, ⁶³Cu, ⁶⁶Zn, ⁶⁹Ga, ⁷²Ge, ⁷⁵As, ⁸²Se, ⁸⁹Y, ⁹³Nb, ⁹⁵Mo, ¹⁰³Rh, ¹⁰⁵Pd, ¹⁰⁷Ag, ¹¹¹Cd, ¹¹⁵In, ¹¹⁸Sn, ¹²¹Sb, ¹²⁵Te, ¹³⁹La, ¹⁸²W, ¹⁹⁵Pt, ¹⁹⁷Au, ²⁰²Hg, ²⁰⁸Pb, ²⁰⁹Bi, ²³²Th, ²³⁸U, all at 10 ms dwell times and with a total cycle time of 0.442 seconds.

The LA-ICP-MS quantification requires that elements are measured as ratios relative to an internal standard of known concentration. Therefore, all elements were measured using Au as the internal standard. Integration of the standard and sample signals was achieved with the SILLS software

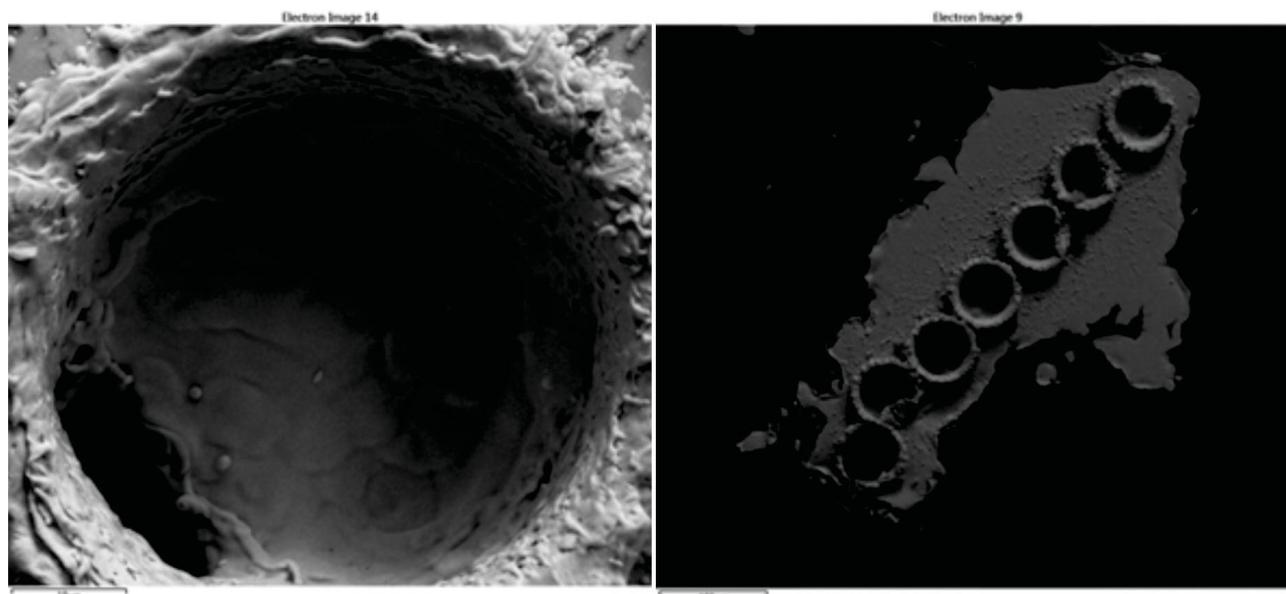


Figure 2. Scanning electron microscope images of laser-ablation pits in gold after ablation for 150 laser pulses. Penetration depth into the gold is approximately 100 µm. Re-precipitated metal forms a rim around the ablation pit, but the majority of material is transported as an aerosol to the ICP-MS. The image on the left shows where the laser has penetrated through the gold grain (hole at bottom left). On the right, a series of closely spaced 50 µm pits shows how spatial compositional variations in a single gold grain could be determined.

package (Allan, 2005; Guillong et al., 2008). The London Bullion Market Association Reference Standard AuRM2 was used as the primary standard for Ag, Al, As, Bi, Cr, Cu, Fe, Mn, Ni, Pb, Pd, Pt, Rh, Sb, Se, Sn, Te and Zn, with the

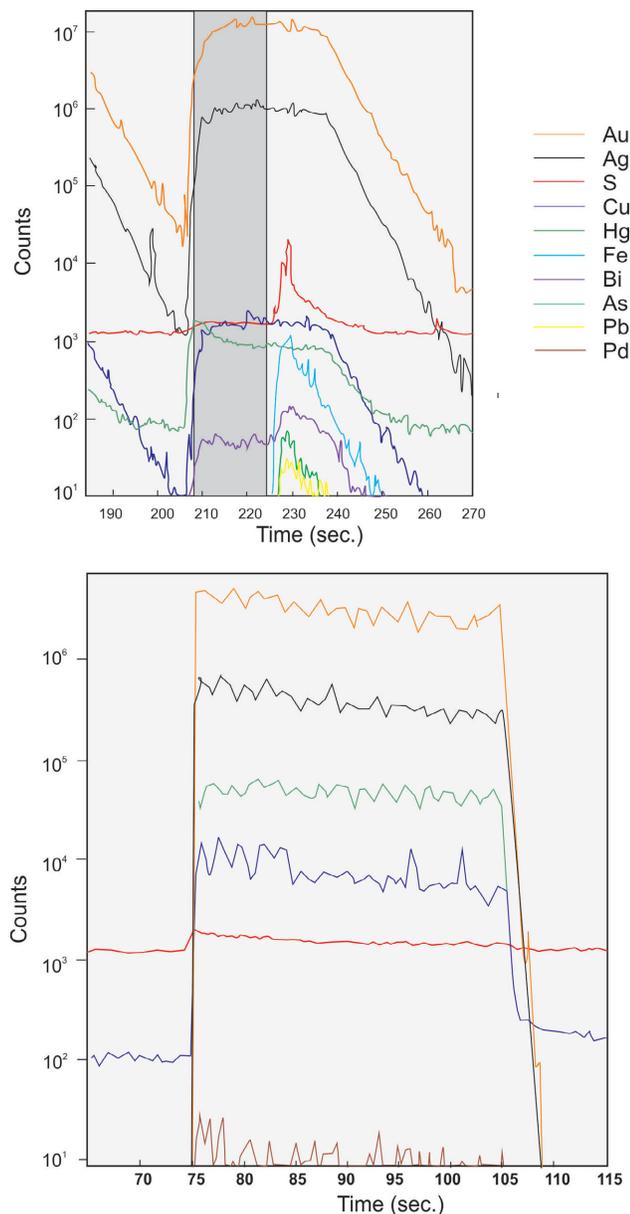


Figure 3. Visualization of ablation of a gold grain with 150 laser pulses over 30 seconds using the SILLS software package (Allan, 2005; Guillong et al., 2008). The elemental traces are a depth profile through the gold going down to approximately 100 μm : **a)** ablation-depth profile initially shows elements in gold but then ablates a sulphide inclusion; with SILLS, it is possible to integrate the gold separately from the inclusion, as the shaded area indicates; in the gold area, the elements are (from bottom to top) Bi, Hg, Cu, S, Ag and Au and, in the inclusion, they are (from bottom to top) Pb, As, Bi, Fe, Hg, Cu, S, Ag and Au; the elements Hg, Cu, Ag and Au do not vary as the inclusion is ablated, so the inclusion is composed of Bi, As, Pb, Fe and S; **b)** ablation-depth profile of a gold grain without inclusions; the elements shown (from bottom to top) are Pd, S, Cu, Hg, Ag and Au; for each element, the signals are quite constant and parallel; in this case, the period of ablation would be integrated and processed with SILLS.

remaining elements calibrated against NIST 610 glass, again using Au as the internal standard element. However, AuRM2 was not suitable for accurate determination of the Ag/Au ratio, as the Ag/Au ratio of the standard is 9.96^{-5} , whereas most of the gold grains have Ag/Au ratios of 0.25 to 0.66 (corresponding to ratios of 80:20 to 60:40 percent Au:Ag, respectively). Hence, this would require extrapolating the calibration many orders of magnitude above the value of the standard. The NIST 610 standard has a Ag/Au ratio of 0.106, which is closer to the sample values and did produce more accurate results. The Ag/Au ratio used in the final quantification was calibrated against NIST standard 481, which is a set of Au-Ag wires ranging in composition from pure Au and Ag to intermediate compositions of 80:20, 60:40 and 40:60 percent Au:Ag respectively. The 80:20 standard was used for quantification and, despite the difference in matrix and in the concentration of both elements, gave a calibration that was almost identical to that obtained using NIST 610. Determining the calibration for Hg used the USGS synthetic sulphide standard MASS-1, as Hg is not present in the NIST standards or the AuRM2 standard. In this instance, the calibration was based on using Ag as the internal standard element, as there is no Au in MASS-1, and manually extracting the counts per second ratio for Hg/Ag from the SILLS output to use with the Hg/Ag wt./wt. ratio of the standard. A combination of calibrations based on the S/Au from NIST 610 and S/Ag from MASS-1 (calibration procedure was the same as for Hg/Ag) was used to determine the S wt./wt. ratio in the gold grains.

Standards SRM-610 and AuRM2 were used to monitor instrumental drift, which was found to be insignificant over each day's analyses. The slope of the calibration graphs converting the counts per second ratios to weight ratios was consistent during the 2–3 week analysis period, indicating the stability of the instrumentation. Using SILLS, it was possible to determine the wt./wt. ratios of elements in the samples using either NIST 610 or AuRM2 as the calibration standard. Element concentrations of the samples, with the exception of Pd and Pt, were within 10% of each other, which indicates that matrix effects are negligible using this analytical system.

Processing of the ICP-MS output using SILLS produces a series of background-corrected wt./wt. ratios for each of the elements analyzed relative to the internal standard element, Au, which is given a value of 1. If the value of the internal element is known for each area ablated, then that can be input instead and the concentration of the other elements will be output as concentrations; however, the concentration of Au in the grains is unknown. The approach used here was to sum the wt./wt. ratios of all the elements/Au that were above the detection limit and divide 1 000 000 ppm (100%) by that number, which when multiplied by the individual element/Au ratio gives the ppm value for that element. In effect, element concentrations were determined by

normalizing the total to 100%, thereby eliminating the need for a true internal standard, because everything with a significant concentration has been analyzed and the total will be 100%.

Figure 4 compares the alloy compositions of gold grains from a low-sulphidation epithermal deposit (Black Dome) with those from the Similkameen River placer adjacent to Copper Mountain. Results are included for Au, Ag, Hg and Cu obtained using both electron microprobe and LA-ICP-MS. In both examples, the median and distribution of analytical results are quite comparable except for Cu from the epithermal deposit, where the LA-ICP-MS data are at significantly lower concentrations. However, this is likely to be a due to the microprobe analysis having a detection limit

that is much higher (~300 ppm), so it cannot accurately determine lower concentrations. When the Cu concentration is greater, as in the porphyry deposit, both methods give very similar results. Thus, the good comparisons mean that the analytical approach is valid and the LA-ICP-MS data are comparable with EMP analyses.

Initial Results

This paper has detailed the application of LA-ICP-MS to the analysis of gold grains and shown that the amount of additional data that can be obtained is greater than was possible using only the electron microprobe as the analytical method of choice. The analysis (to date) of 776 grains for 36 elements from different localities and different deposit

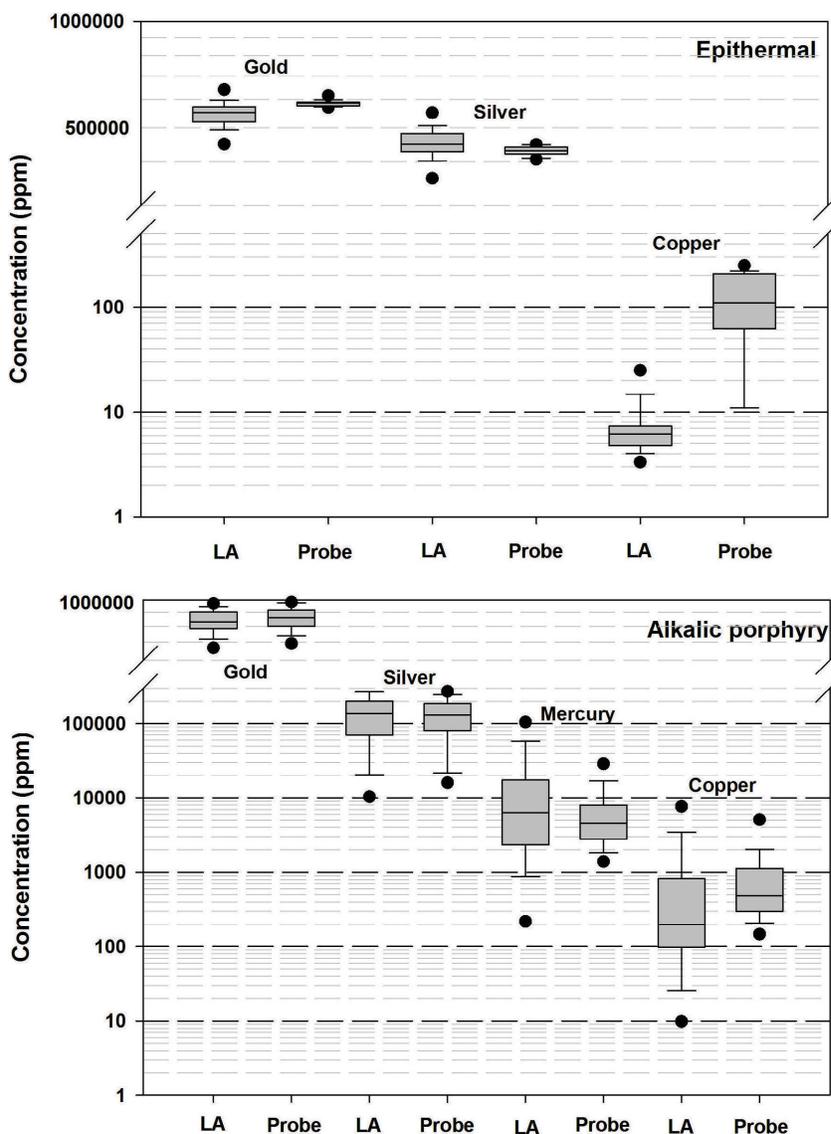


Figure 4. Comparison of the Au, Ag, Hg and Cu concentrations in placer-gold populations from two deposit types by electron microprobe and LA-ICP-MS. The statistical distribution of concentrations (median, box is 25th to 75th percentile, upper and lower lines are 5th and 95th percentiles) compare well except for Cu in the epithermal deposit. However, the microprobe analysis for Cu is at the detection limit for the technique.

types in BC has made it possible to define the elements that are most commonly present at sufficient concentrations to be used as potential discriminators of the origins of the gold. Figures 5–7 show that it is possible to interrogate the dataset at low concentrations of various elements to obtain useful information. However, a full interpretation of the data is not possible at present owing to the incomplete dataset (Table 1).

In Figure 5, bivariate plots of the major elements in the gold are shown for all the grains analyzed so far, differentiated on the basis of the deposit type from which the gold originated. The alkali porphyry deposits have, in general, the highest concentrations of elements other than the Au and Ag that dominate the gold-grain composition as a binary mixture. The alkali porphyry deposits plot below a binary mixing line due to the high concentrations of Hg, up to

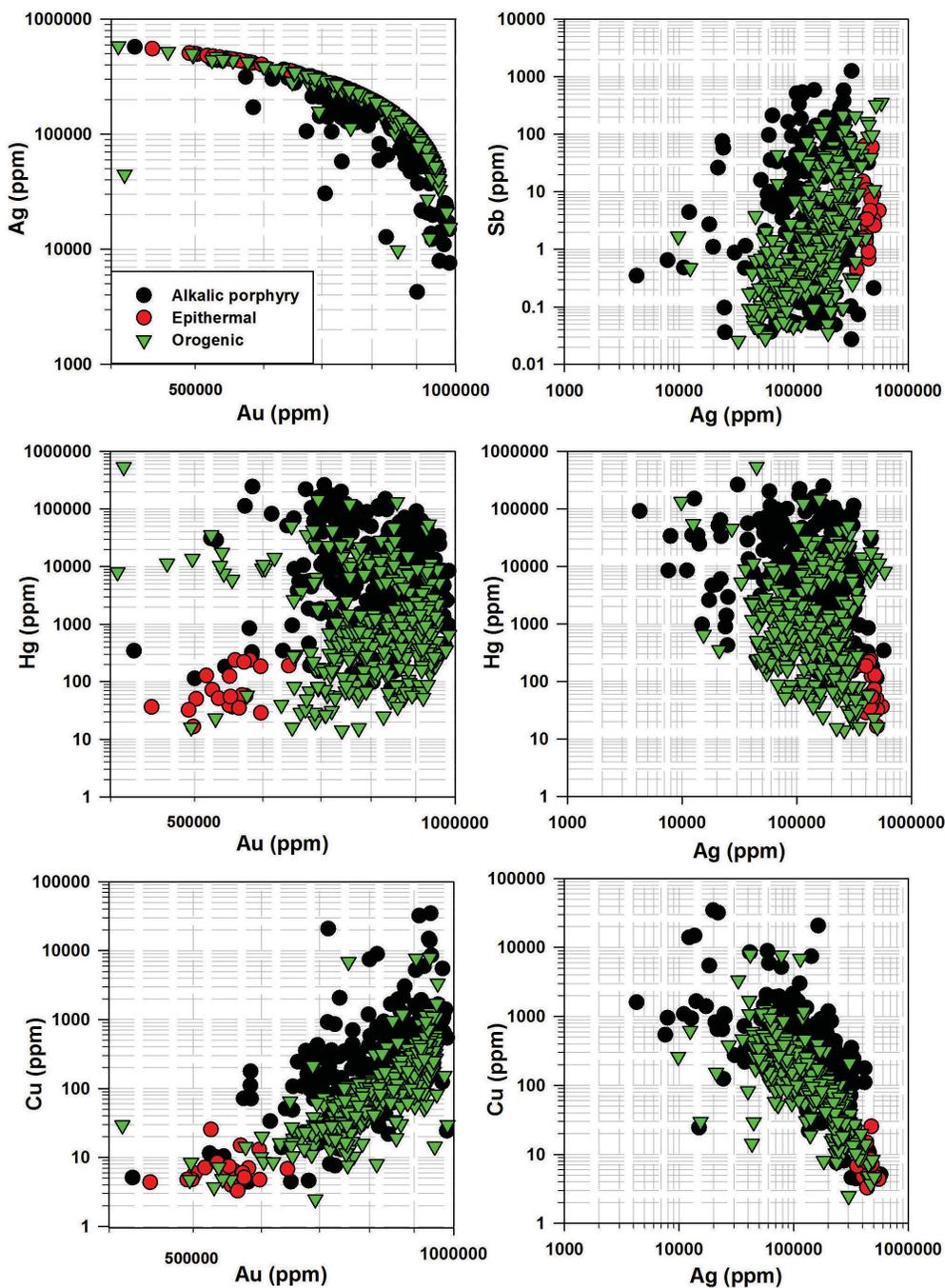


Figure 5. Major elements in all gold grains analyzed, differentiated on the basis of the type of deposit from which the placer grains originated.

10%, in these grains. There are reasonably good negative correlations of Hg with Au and Ag, over a large range in Hg concentrations, which is indicative of Hg replacing both Au and Ag in the porphyry gold grains. The dataset available that relates to epithermal deposits is relatively restricted when compared to the other two types. Nevertheless, the initial indication is that, for these types of deposit, there may be distinction based on the higher Ag and the low Cu and Hg concentrations. The number of gold grains from orogenic deposits analyzed is relatively large and some clearly defined trends have emerged. The majority of gold grains are binary Au and Ag mixtures, with these elements making up well over 99% of the composition, a result that is well known from previous alloy studies using EMP. In general, other elements are present at lesser concentrations than the alkalic porphyry deposits but greater than the single epithermal deposit studied here. There is a good positive correlation of Ag and Sb, and good negative correlations of Ag with Cu and Hg. These trends have not been previously observed in EMP datasets because of the higher detection limits. It is encouraging, at this level of data interpretation, that different sources of gold grains do seem to have observable differences when looking at the dataset as a whole. The observed correlations from measurement of trace elements at low concentrations show that these are not just random analyses, but may be related to processes during gold deposition.

In Figure 6, three individual deposits (Spanish Creek, Black Dome and Similkameen) have been chosen as examples of gold derived from orogenic, low-sulphidation epithermal and alkalic porphyry systems, respectively. Although some differences in alloy compositions can be identified in the EMP data (and corresponding inclusion assemblages), a number of further differences can be observed in the suite of minor elements whose concentrations have been measured using LA-ICP-MS. Gold from the Similkameen placer (alkalic porphyry related) shows the most complex elemental signatures and with trace elements at the highest concentrations. Gold from the Black Dome deposit contains fewer elements and at lower levels, whereas the signature of gold from Spanish Mountain (orogenic) falls midway between the other two. Three elements are worthy of particular attention: Hg, Cu and Pd. Concentrations of Hg in gold alloy from the alkalic porphyry system are around ten times higher than in the gold from Spanish Mountain, which in turn exhibits Hg concentrations ten times those of the gold from Black Dome. The detection limit for Hg by EMP is around 0.3%, so the use of LA-ICP-MS allows measurement and interpretation of Hg in the alloy at far lower levels. Copper concentrations were generally highest in gold from the alkalic porphyry system, although most grains from this sample suite and the Spanish Mountain suite returned similar values for Pd; however, some individual grains from the Similkameen River exhibited far

higher Pd values. Palladium was absent in the gold from Black Dome, where Cu concentrations were also very low.

Figure 7 compares LA-ICP-MS analyses of three placer samples taken in the vicinity of the Copper Mountain alkalic porphyry. The Similkameen River sampling locality was immediately downstream of the main ore zone, whereas those at Friday and Whipsaw creeks were more distal. The three sets of analyses look similar, which is consistent with derivation from similar distal sources surrounding the porphyry. Minor deviations in signature (e.g., elevated Hg and Cd in the Similkameen River sample) are likely to be a consequence of element zonation superimposed on the different catchments. The As content of some gold grains from Whipsaw Creek was higher than those encountered elsewhere. The reasons for this difference remain unclear, although they are clearly related to a subpopulation of grains specific to that drainage. However, the overall similarity between the three signatures supports the assertion that the technique yields reproducible results from individual primary sources of mineralization.

Preliminary Observations and Concluding Remarks

Successive ablation of natural gold yields datasets that reveal whether specific elements are present as alloy components or as inclusions. The ability of the SILLS software to visualize and filter out these modes of occurrence has enabled the authors to establish which elements have the potential to act as discriminators when comparing alloy compositions. Consideration of the relatively small number of data points described in this paper has highlighted advantages of gold alloy analysis by LA-ICP-MS. The differences between alloy signatures in gold from different deposit types previously identified by EMP analysis are evident in the LA-ICP-MS data, but the quantitative analysis of Cu, Hg and Pd at trace levels permits additional interrogation of these datasets. Most importantly, the use of LA-ICP-MS has identified the potential for other elements (e.g., Sb) to be used as discriminators and the ability to spot trends in element ratios where analyses were close to the detection limit by EMP. Regardless of the preliminary nature of the data, it appears that there are reproducible compositional similarities between populations of gold derived from the same source, and that differences exist between signatures of gold from different source types. The authors stress that, as yet, there are insufficient data to establish whether such differences are generic or a consequence of specific environments of mineralization. Ongoing studies will seek to clarify this question while also focusing on the detailed examination of the new datasets in the context of existing characterization of the microchemical signatures.

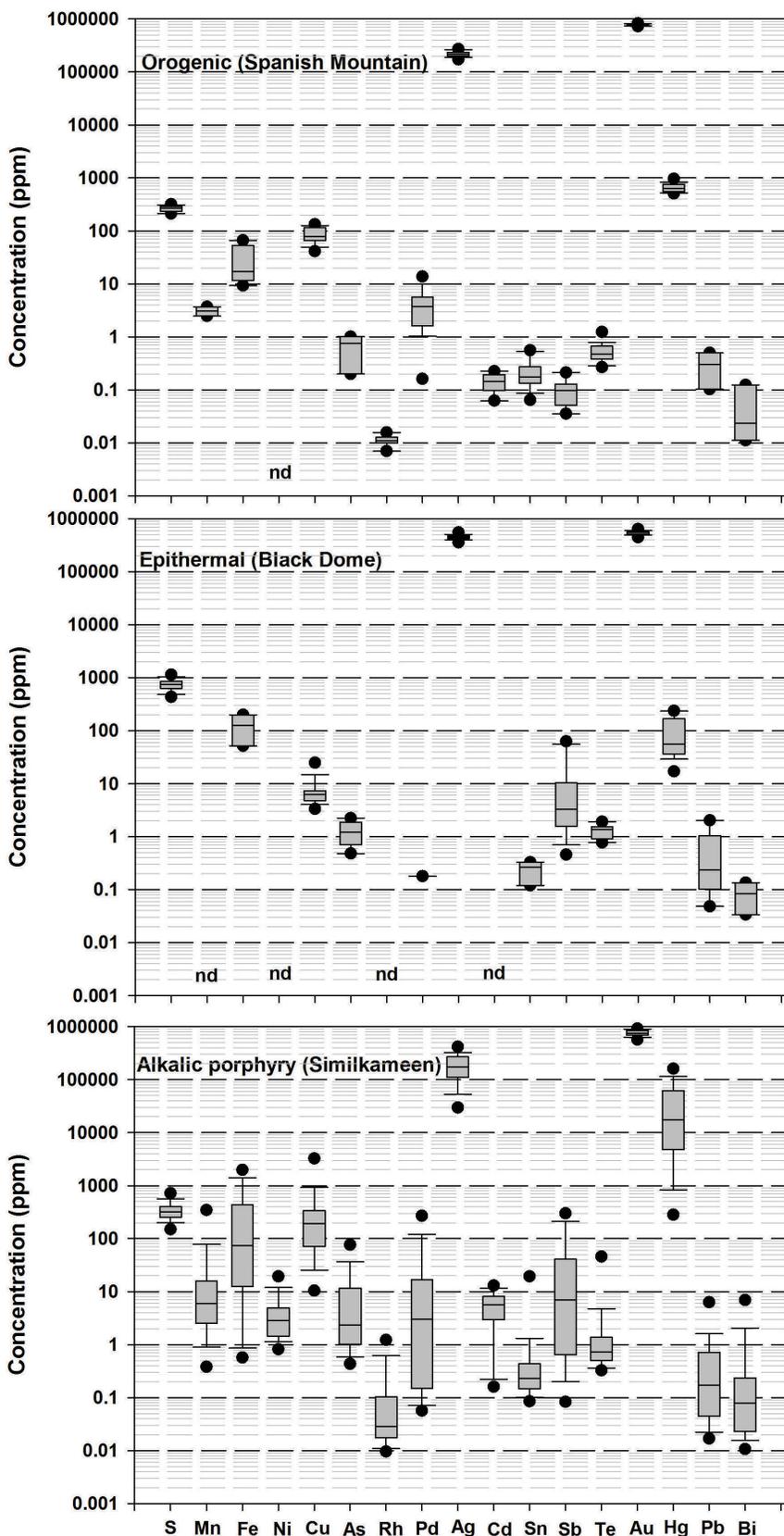


Figure 6. Analyses of the most common elements from three deposits that are representative of the different styles of mineralization. In this initial presentation, it is clear that there are significant differences in the concentrations of elements, other than Au and Ag, from the three deposit types.

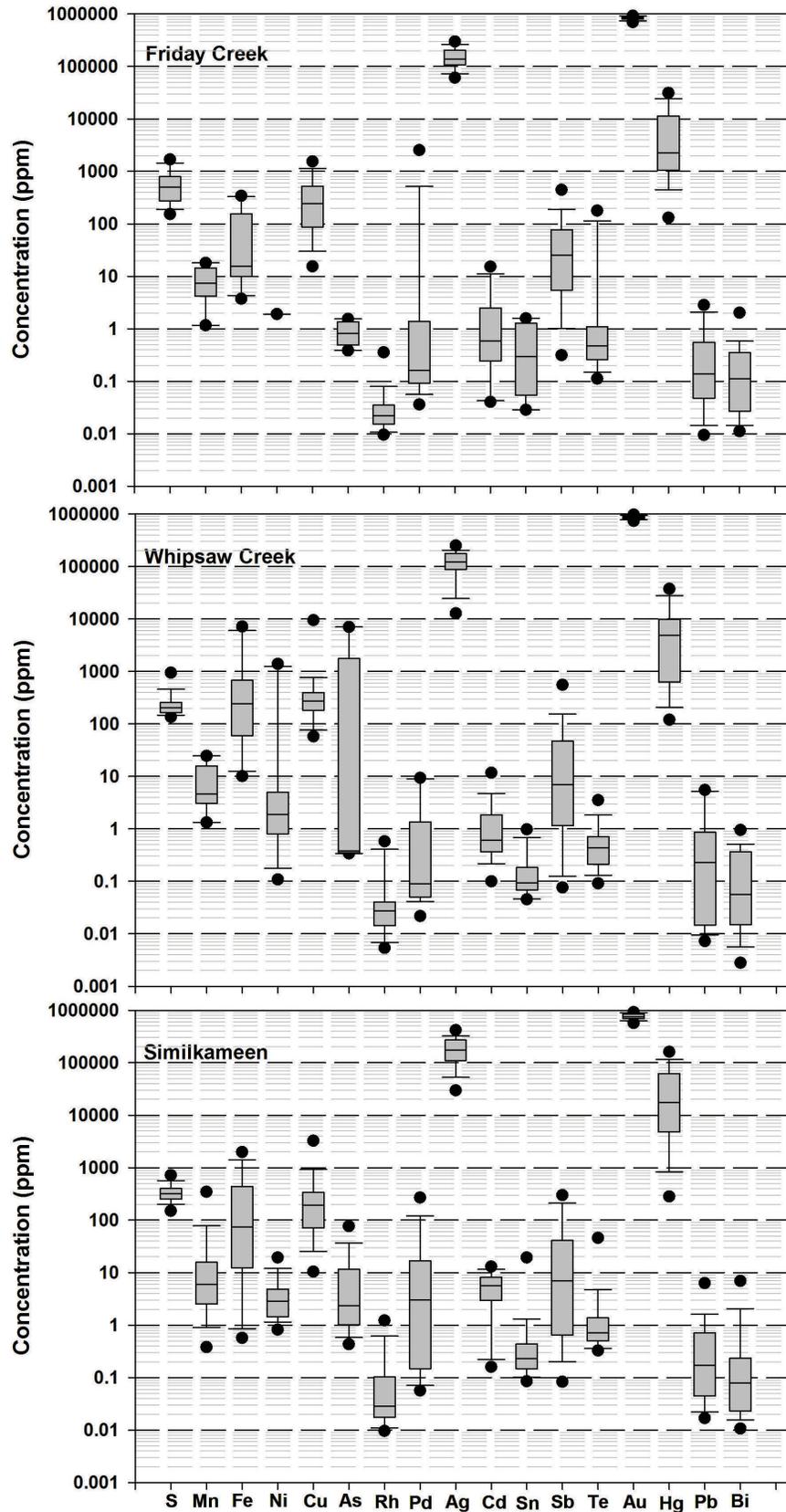


Figure 7. Analyses of placer grains from different streams in the vicinity of the Copper Mountain porphyry. Elements shown are those that are most prevalent in the grains. In general, the analyses show a good degree of similarity, but Hg, for example, is much higher at Similkameen than the other two placers.

The initial results of the study reported here have built upon the foundations of gold compositional work established using microchemical characterization. British Columbia provides an excellent testing ground to develop this methodology, by virtue of the diverse nature of gold mineralization and the overall gold endowment. Ongoing studies will constitute a novel approach to illuminating regional gold metallogeny through the studies of detrital gold, which is relevant not only to a better understanding of Cordilleran geology but to application in comparable areas of exploration interest globally. Consequently, the authors will continue to evaluate the possibility of establishing a low-cost, early-stage exploration methodology that would form a valuable addition to the suite of techniques available to explorationists in BC.

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References

- Allan, M.M. (2006): Hydrothermal processes in the Mouth Leyshon Intrusive Complex, Australia: microanalytical insights; Ph.D. thesis, University of Leeds, Leeds, United Kingdom, 321 p.
- Antweiler, J.C. and Campbell, W.L. (1977): Application of gold compositional analyses to mineral exploration in the United States; *Journal of Exploration Geochemistry*, v. 8, p. 17–29.
- BC Geological Survey (2016): MINFILE BC mineral deposits database; BC Ministry of Energy and Mines, URL <<http://minfile.ca>> [November 2016].
- Bouzari, F., Hart, C.J.R., and Barker, S. (2016): Hydrothermal alteration revealed by apatite luminescence and chemistry: a potential indicator mineral for exploring covered porphyry copper deposits. *Economic Geology*, v. 111, pp. 1397–1410.
- Bouzari, F., Hart, C.J.R., Barker, S. and Bissig, T. (2010): Porphyry indicator minerals (PIMs): exploration for concealed deposits in south-central British Columbia (NTS 092I/06, 093A/12, 093N/01, /14); *in* Geoscience BC Summary of Activities 2009, Geoscience BC, Report 2010-1, p. 25–32, URL <http://www.geosciencebc.com/i/pdf/SummaryofActivities2009/SoA2009_Bouzari.pdf> [October 2016].
- Celis, M.A., Bouzari, F., Bissig, T., Hart, C.J.R. and Ferbey, T. (2014): Petrographic characteristics of porphyry indicator minerals from alkalic porphyry copper-gold deposits in south-central British Columbia (NTS 092, 093); *in* Geoscience BC Summary of Activities 2013, Geoscience BC, Report 2014-1, p. 53–62, URL <http://www.geosciencebc.com/i/pdf/SummaryofActivities2013/SoA2013_Celis.pdf> [October 2016].
- Chapman, R.J. and Mileham, T.J. (2016): Detrital Au grains as indicators of alkalic Cu-Au porphyry mineralization; Geoscience BC, Report 2016-06 (unpublished internal report), 48 p.
- Chapman, R.J., and Mortensen, J.K. (2016): Characterization of gold mineralization in the northern Cariboo Gold District, British Columbia through integration of compositional studies of lode and detrital gold with historical placer production: a template for evaluation of orogenic gold districts; *Economic Geology*, v. 111, p. 1321–1345.
- Chapman, R.J., Leake, R.C., Moles, N.R., Earls, G., Cooper, C., Harrington, K. and Berzins, R. (2000): The application of microchemical analysis of gold grains to the understanding of complex local and regional gold mineralization: a case study in Ireland and Scotland; *Economic Geology*, v. 95, no. 8, p. 1753–1773.
- Chapman, R.J., Mortensen, J.K., Crawford, E. and LeBarge, W. (2010): Microchemical studies of placer and lode gold in the Klondike District, Yukon, Canada: 1. evidence for a small, gold-rich, orogenic hydrothermal system in the Bonanza and Eldorado Creek area; *Economic Geology*, v. 105, p. 1369–1392.
- Guillong, M., Meier, D.L., Allan, M.M., Heinrich, C. and Yardley, B.W.D. (2008): SILLS – a MATLAB-based program for the reduction of laser ablation ICP-MS data of homogeneous materials and inclusions; *in* Laser Ablation ICP-MS in the Earth Sciences: Current Practices and Outstanding Issues, P. Sylvester (ed.), Mineralogical Association of Canada, Short Course 40, p. 328–333.
- Kelley, K.D., Eppinger, R.G., Lang, J., Smith, S.M and Fey, D.L. (2011): Porphyry Cu indicator minerals in till as an exploration tool: example from the giant Pebble porphyry Cu-Au-Mo deposit, Alaska, USA; *Geochemistry: Exploration, Environment, Analysis*, v. 11, p. 321–334.
- Knight, J.B., Mortensen, J.K. and Morison, S.R. (1999): Lode and placer gold composition in the Klondike District, Yukon Territory, Canada: implications for the nature and genesis of Klondike placer and lode gold deposits; *Economic Geology*, v. 94, p. 649–664.
- McTaggart K.C. and Knight, J. (1993): Geochemistry of lode and placer gold of the Cariboo District, BC; BC Ministry of Energy and Mines, Open File 1993-30, 25 p.
- Mortensen, J.K. and Chapman, R. (2010): Characterization of placer- and lode-gold as an exploration tool in east-central British Columbia (parts of NTS 093A, B, G, H); *in* Geoscience BC Summary of Activities 2010, Geoscience BC, Report 2011-1, p. 109–122.
- Pisiak, L.K., Canil, D., Grondahl, C., Plouffe, A., Ferbey, T. and Anderson, R.G. (2015): Magnetite as a porphyry copper indicator mineral in till: a test using the Mount Polley porphyry copper-gold deposit, south-central British Columbia (NTS 093A); *in* Geoscience BC Summary of Activities 2014, Geoscience BC, Report 2015-1, p. 141–150.
- Plouffe, A., Ferbey, T., Anderson, R.G., Hashmi, S. and Ward, B.C. (2013): New TGI-4 till geochemistry and mineralogy results near the Highland Valley, Gibraltar, and Mount Polley mines, and Woodjam District: an aid to search for buried porphyry deposits; Geological Survey of Canada, Open File 7473, 58 p.
- Wrighton, T.M., (2013) Placer gold microchemical characterization and shape analysis applied as an exploration tool in western Yukon; M.Sc. thesis, The University of British Columbia, 140 p.